Collection of Photoelectrons from a CsI Photocathode in Triple GEM Detectors

C.Woody, B.Azmoun, A.Caccavano, Z.Citron, M.Durham, T.Hemmick, J.Kamin, M.Rumore

***Abstract*—A study has been made of the parameters affecting the extraction and collection of photoelectrons from the surface of a CsI photocathode in a triple GEM detector. The purpose of this study was to optimize the photoelectron collection efficiency and GEM operating conditions for the PHENIX Hadron Blind Detector (HBD) at RHIC. The parameters investigated include the electric field at the surface of the photocathode, the voltage across the GEM, the electric field below the GEM, the medium into which the photoelectrons are extracted (gas or vacuum), and the wavelength dependence of the extraction efficiency. A small, calibrated light source, or "scintillation cube", was used to measure the photoelectron yield from the CsI photocathode using ^{241}Am particles to produce scintillation light in CF_4 and an ^{55}Fe source to measure the GEM gas gain. The absolute scintillation light yield (photons/MeV) in CF_4 gas was also determined using a CsI photocathode GEM detector. Results are presented on the study of the parameters affecting the photoelectron collection efficiency, the construction and calibration of the scintillation cube, and the measurement of the absolute scintillation light yield in CF_4.**

I. INTRODUCTION

THE quantum efficiency and photoelectron collection efficiency for CsI photocathodes has been studied by a number of authors [1-5]. However, the measurements have shown conflicting results, particularly regarding the maximum number of photoelectrons that can be extracted from a CsI photocathode surface into various gases and subsequently transported into the gain region of a GEM detector. This process is of great importance for the performance of the PHENIX Hadron Blind Detector (HBD), which uses CsI photocathode GEM detectors to detect Cherenkov photons produced by relativistic particles in a CF_4 radiator in heavy ion collisions at RHIC [6]. The purpose of this study was to investigate the parameters affecting the photoelectron collection efficiency for CsI photocathode GEM detectors operated in pure CF_4 in order to better understand this process and to optimize the performance of the HBD.

The HBD utilizes an array of triple GEM detectors where the top GEM has a ~ 200 nm thick CsI photocathode layer deposited on its top surface. A mesh electrode above this surface is used to control the field above the photocathode. It can be biased such that charge produced in the gap between the mesh and the top GEM is collected by the GEM (Forward Bias) or by the mesh (Reverse Bias). The detector is operated in pure CF_4, where the CF_4 acts as both the Cherenkov radiator and as the operating gas for the GEMs.

The main factor affecting the production of photoelectrons from the photocathode is the quantum efficiency. This can be measured in vacuum in a parallel plate configuration where all photoelectrons are collected by the mesh. Fig. 1 shows the quantum efficiency measured as a function of wavelength for our typical CsI photocathodes.

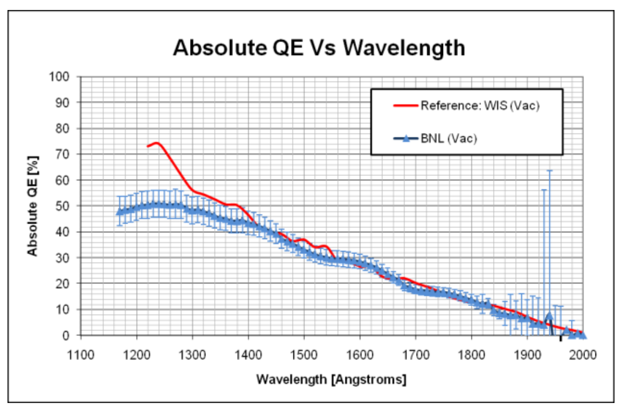

Fig. 1. Quantum efficiency of typical CsI photocathodes measured in vacuum in parallel plate collection mode.

The photoelectron collection efficiency depends on the electric field in the collection gap, and quickly reaches 100% in vacuum, as shown in Fig 2. However, in the presence of gas, the collection efficiency is reduced due to the backscattering of electrons off gas molecules. Fig 2 shows that in CF_4, the collection efficiency reaches a plateau value of ~ 80% at a field of ~2 kV/cm, whereas for Ar, the collection efficiency is lower and there is no plateau for fields less than 2.5 kV/cm. This is believed to be due to the effect of the vibrational modes of excitation of CF_4 molecules at low electron energies [5]. We note that the same efficiency is measured for different drift gap

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B.Azmoun, A.Caccavano and C.Woody are with Brookhaven National Laboratory, Upton, NY (E-mail: woody@bnl.gov).

M.Rumore is with Worcester Polytechnic Institute, Woster, MA

Z.Citron, M.Durham, T.Hemmick and J.Kamin are with Stony Brook University, Stony Brook, NY.

widths, indicating that the loss of electrons takes place close to the photocathode surface and is therefore not due to attachment or recombination of electrons during transport.

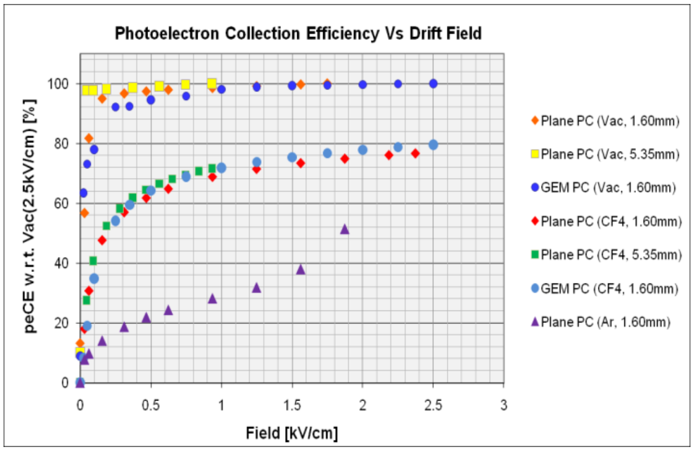

Fig. 2. Photoelectron collection efficiency as a function of electric field in parallel plate collection mode for vacuum, CF_4 and argon.

The process of backscatter and transport losses and its effect on the photoelectron collection efficiency in CF_4 and other gases has also been investigated using a detailed Monte Carlo simulation [5]. They predict that the collection efficiency depends not only on the field, but also on the wavelength of the incident light. Our measurements agree qualitatively with these predictions, as shown in Fig. 3, which indicates that the collection efficiency decreases with increasing photon energy.

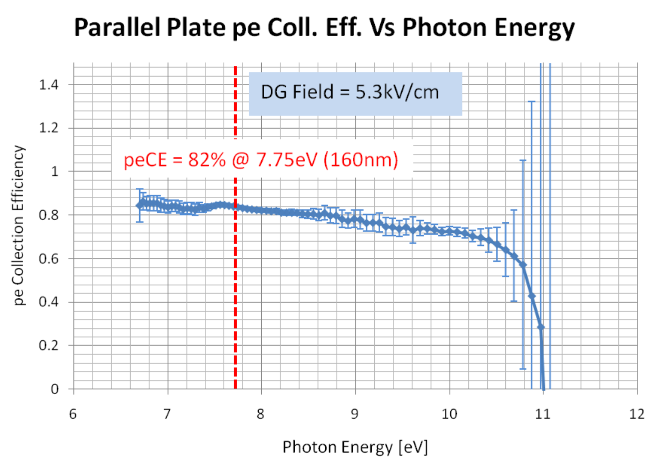

Fig. 3. Photoelectron collection efficiency for different incident wavelengths.

We define the photoelectron collection efficiency for a light sensitive GEM detector to be the ratio of the number of photoelectrons that are collected and subsequently amplified in the gain region of the GEM detector to the number that are produced at the photocathode for a given quantum efficiency. We assume that the overall photoelectron collection efficiency can be factorized into two components: an *extraction efficiency* that gives the fraction of photoelectrons that are extracted from the surface of the photocathode without immediate recombination, and a *transport efficiency,* which gives the probability that a photoelectron, once extracted, is successfully transported through the gas to the gain region of the GEM. The overall efficiency may then be expressed as the product of the two terms $\varepsilon_{CE}(\boldsymbol{E},\lambda) = \varepsilon_{EE}(\boldsymbol{E},\lambda) \cdot \varepsilon_{TE}(\boldsymbol{E})$. It is further hypothesized that the extraction efficiency depends on both the extraction field, ***E***, and on the wavelength of the incident photons, λ, whereas the transport efficiency only depends on the field.

The overall photoelectron efficiency was determined by illuminating a CsI photocathode triple GEM detector with a calibrated light source for which the emitted photon flux was known, and therefore the number of photoelectrons produced could be determined using the known quantum efficiency of the photocathode. The overall collection efficiency was then given by the ratio of the number of photoelectrons contributing to the final GEM signal to the initial number produced:

$$\varepsilon_{CE} = Npe(collected)/Npe(produced)$$

A custom calibrated light source was designed and constructed to provide a known flux of photons to illuminate the photocathode. A sketch of the light source, or "Scintillation Cube", is shown in Fig. 4. Inside the cube, ^{241}Am alpha particles traverse ~ 9 mm of CF_4 and produce scintillation light that emanates from a reflective cavity, thus providing a constant flux of 160 nm photons. A silicon surface barrier detector (SBD – Ortec Model BU-014-025-100) provides a signal to trigger on the alpha particle. In addition, the amplitude of the SBD signal provides information about the total energy deposited by the alpha within the gas. By initially determining the amplitude of this signal in vacuum, which corresponds to the initial energy of the alpha (5.48MeV), the SBD signal amplitude may be calibrated in terms of energy. The total energy deposited within the gas is then simply the

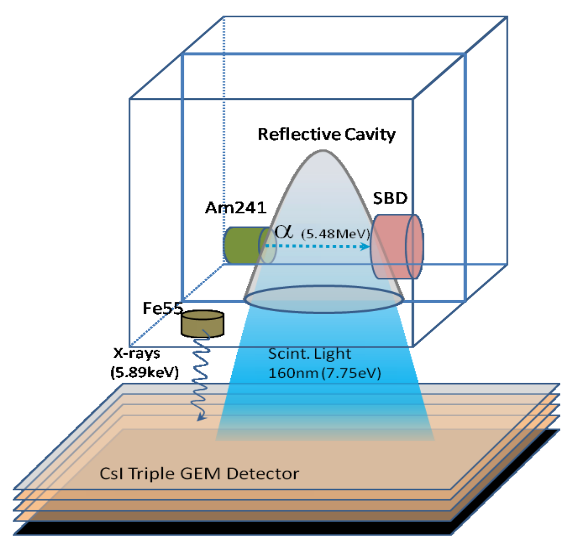

Fig. 4. Calibrated Light Source: "Scintillation Cube", illuminating a CsI-Photocathode-GEM-detector.

initial energy of the alpha minus the energy deposited in the SBD. The scintillation cube also includes an ^{55}Fe source that simultaneously illuminates the GEM with 5.89 keV X-rays and allows a determination of the gas gain of the GEM.

The absolute photon flux emanating from the scintillation cube was measured using a calibrated CsI photocathode PMT (Hamamatsu R6835). Both the quantum efficiency and the gain of the PMT were provided by the manufacturer. However, we also made our own measurements of these quantities. The quantum efficiency was measured using another PMT of the same type as a reference, and was found to match the factory value. The PMT gain was checked by obtaining the single photoelectron pulse height spectrum from the dark current noise and assigning the mean charge output to be that of a single photoelectron, which agreed fairly well with the factory gain. The value obtained for the flux was $N_\gamma = 9.6 \pm 0.5$ γ/MeV, and the number of photoelectrons produced on the GEM CsI photocathode is then given by:

$$Npe(produced) = N_\gamma * T_{mesh} * T_{GEM} * QE_{CsI(160nm)}$$

where T_{mesh} and T_{GEM} are the mesh and GEM transparency respectively, and $QE_{CsI(160nm)}$ is the quantum efficiency of the plane CsI photocathode measured at 160 nm in vacuum. Using values for $T_{mesh} = 0.80$, $T_{GEM} = 0.83$, and $QE_{CsI(160nm)} = 0.23$ gives:

$$Npe(produced) = 6.3 \pm 0.3 \text{ pe/MeV}$$

The number of photoelectrons collected was determined using two different methods. The first consisted of dividing the mean value of the total charge collected by the GEM pad (expressed in terms of electrons) by the gas gain, measured using the ^{55}Fe source inside the cube. The second used an analysis of the shape of the GEM pulse height spectrum. This method assumes that the observed spectrum originates from a primary photoelectron distribution which follows Poisson statistics, which is then convoluted with a Polya distribution representing the gain fluctuations, along with a Gaussian pedestal distribution. The analysis is carried out by generating a series of Monte Carlo simulated data in which the mean of the primary Poisson distribution is allowed to vary. By performing a Chi square analysis, the simulated data was then fit to the actual data in order to determine the best fit. The mean of the primary photoelectron distribution corresponding to the best fit was then taken to be the true *Npe*.

We attempted to determine the particular Polya function that represents the gain probability distribution for a single electron within a triple GEM detector. The following parameterization of the Polya function [7] was used, expressed in terms of the Polya parameter θ :

$$P(g) \cong \left\{(1+\theta)\frac{g}{g_o}\right\}^{\theta} e^{-(1+\theta)\frac{g}{g_o}}$$

where g is the gain of a single photoelectron, and g_o is the mean gain of the detector. Since we are only interested in the shape of the fluctuation in gain, g_o was set equal to 1 for our calculations. By repeating the fitting procedure described above, but making the Polya parameter a free variable and using the number of primary photoelectrons from the mean method, we arrive at a positive value of $\theta = 0.33 \pm 0.02$, while operating the GEM at an *effective* gain of approximately 8×10^3. Although the detector type, the avalanche gas and the gas gain all influence the determination of θ according to [8], our value is relatively in close agreement with the values suggested for a wire chamber operated in CH_4 at a gain of 3.5×10^3, where $\theta = 0.38$ [9], and in CF_4 at a gain of 7.5×10^5, where $\theta = 0.21$ [7]. Due to closer similarities in gain, we have used the value of $\theta = 0.38$ in our fitting method calculations above, which proved to be a reasonable estimate. It should be noted, however, that the Polya parameter only weakly influences the determination of the number of primary photoelectrons in our fits (e.g., changes in θ on the order 30% alter the value of photoelectrons by only a few percent.).

The gain method and fitting method resulted in *Npe* values that differed by more than their respective statistical errors, and the difference was taken to be a measure of the systematic error. A simple, non-weighted average was taken as the best estimate of *Npe(collected),* and an estimate of the total error was taken to be half of the difference between the two values, giving $Npe(collected) = 4.2 \pm 0.2$ pe/MeV. The photoelectron collection efficiency is then given by the ratio *Npe(collected)/Npe(produced):*

$$\varepsilon_{CE}(E_o, 160nm) = 4.2 \pm 0.2 \;/\; 6.3 \pm 0.3 = 0.66 \pm 0.06.$$

Using this value for the overall collection efficiency, one can determine the transport efficiency if the extraction efficiency is known. If we assume that the overall collection efficiency measured in parallel plate collection mode is the same as the extraction efficiency in GEM mode, then we can use the results given in Figure 3 as an estimate of the extraction efficiency. At 160 nm (7.75eV), this gives a value for $\varepsilon_{EE}(5kV/cm, 160nm) = 0.82 \pm 0.03$. Note that this corresponds to an electric field at the surface of the GEM of ~ 5 kV/cm, although the *average* field in the drift gap is only ~ 0.4 kV/cm. This gives a value for the transport efficiency of:

$$\varepsilon_{TE}(E_o) = \varepsilon_{CE}(E_o, 160nm) \;/\; \varepsilon_{EE}(5kV/cm, 160nm) = 0.80 \pm 0.08$$

The fact that the transport efficiency is less than one implies that there is a loss of photoelectrons after they have been extracted from the photocathode**.** This loss must therefore occur after the electrons have traveled several mean free paths away from the photocathode. The results shown in Fig. 2 rule out loss mechanisms such as attachment or recombination resulting from the traversal of photoelectrons through the bulk volume of gas. However, it is possible that the observed loss of photoelectrons during transport could be due to a process similar to that caused by backscattering, namely, scattering of electrons back towards the photocathode due to diffusion. As photoelectrons leave the photocathode and head toward the GEM holes, they remain quite close to the photocathode surface. Many photoelectron trajectories are within only a few tens of microns from the photocathode, which is comparable to the mean free path for an elastic collision in CF_4. Hence, it is quite possible that additional photoelectrons are lost due to scattering and subsequent recombination at the photocathode along their path toward the GEM holes.

II. Scintillation Yield in CF_4

As an additional result, we are able to accurately determine the absolute scintillation light yield in CF_4 using our knowledge of the absolute photoelectron collection efficiency. This measurement uses the experimental setup described in [10] in which the distance the alpha particle travels in CF_4 can be varied, and thereby provides for a differential measurement of the energy deposited in the gas versus the scintillation light produced. By plotting the light yield versus the energy loss by the alpha (dN/dE), the resulting slope of the curve gives the number of scintillation photons emitted for a given amount of energy deposited in the gas. Figure 7 shows the results of this measurement as determined using both the fitting method and the mean method, and indicates that the agreement between the different methods and data sets is quite good. A best fit to the average of the four curves gives a scintillation light yield of 314 ± 15 photons per MeV, where the yield has been normalized to a solid angle of 4π. This value is also consistent with other results published in the literature using a different method of measurement to determine the yield [11].

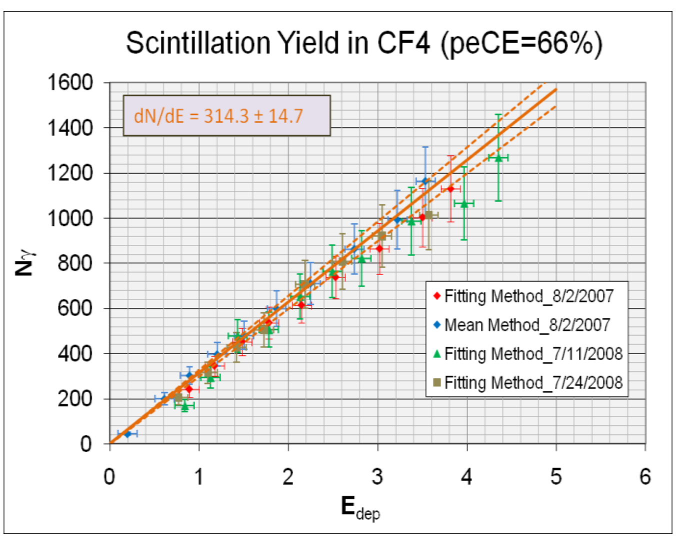

Fig. 7. Scintillation photon yield in CF_4 as a function of energy deposited in the gas. The fitting method and mean methods for determining the yield is described in the text.

III. Summary

The photoelectron collection efficiency of a CsI photocathode triple GEM detector operating in pure CF_4 has been measured. The efficiency is assumed to factorize into two terms: an extraction efficiency that depends only on the probability to extract electrons from the photocathode surface without immediate recombination, and a transport efficiency that reflects the probability for transporting these photoelectrons to the GEM holes where amplification occurs. We find that under our normal GEM operating conditions, the extraction efficiency is 0.82 ± 0.03 and the transport efficiency is 0.80 ± 0.08, leading to an overall collection efficiency of 0.66 ± 0.06. The transport efficiency is considerably lower than in normal parallel plate operation of a CsI photocathode, and could be due to additional recombination losses of photoelectrons at the photocathode during transport. Finally, we have also made a measurement of the scintillation light yield in CF_4 using a CsI photocathode GEM detector and found the yield to be 314 ± 15 photons per MeV.

IV. References

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